

TESTING THE LARGE-SCALE ENVIRONMENTS OF COOL-CORE AND NONCOOL-CORE CLUSTERS
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ABSTRACT

There is a well observed bimodality in X-ray astronomy between cool-core (CC) and non-cool-core (NCC) clusters, but the origin of this distinction is still largely unknown. Competing theories can be divided into *internal* (inside-out), in which internal physical processes transform or maintain the NCC phase, and *external* (outside-in), in which the cluster type is determined by its initial conditions, which in turn lead to different formation histories (i.e., assembly bias). We propose a new method that uses the relative assembly bias of CC to NCC clusters, as determined via the two-point cluster-galaxy cross-correlation function (CCF), to test whether formation history plays a role in determining their nature. We apply our method to 48 ACCEPT clusters, which have well resolved central entropies, and cross-correlate with the SDSS-III/BOSS LOWZ galaxy catalog. We find that the relative bias of NCC over CC clusters is $b = 1.42 \pm 0.35$ (1.6σ different from unity). Our measurement is limited by the small number of clusters with core entropy information within the BOSS footprint, 14 CC and 34 NCC. Future compilations of X-ray cluster samples, combined with deep all-sky redshift surveys, will be able to better constrain the relative assembly bias of CC and NCC clusters and determine the origin of the bimodality.

Subject headings: cosmology: observations — dark matter — galaxies: clusters — large-scale structure of universe

1. INTRODUCTION

Clusters of galaxies grow hierarchically through mergers and accretion of galaxies and groups of galaxies. The gas that falls onto a cluster gravitationally shocks and heats to the observed virial temperature, $T \sim 10^8$ K. In a simplified gravitationally-governed smooth accretion model, clusters should have self-similar entropy profiles (Voit 2005). A decade of high-resolution *Chandra* X-ray observations of cluster gas has unveiled relatively self-similar scaled entropy profiles at virial radius scales ($\sim 1 - 2$ Mpc/h), but the central ($\lesssim 0.1 - 0.2$ Mpc/h) entropies differ considerably. Some clusters show relaxed, cuspy cores with high metallicity and low central temperature and entropy, and are thus named cool core (CC) (Molendi & Pizzolato 2001), whereas others show a more disturbed core with flatter central density and high core entropy, dubbed non-cool core (NCC). Classification schemes vary as CC are hard to define and quantify (Hudson et al. 2010), but the best classifier has been demonstrated to be the central entropy (Cavagnolo et al. 2009). In this scheme, the distribution of core entropies appears to be bimodal (Cavagnolo et al. 2009), although other studies find it to be less pronounced (Panagoulia et al. 2014).

In a purely radiative cooling scenario, the plasma in the cores of clusters is expected to condense in less than a Gyr, with unrealistic cooling rates up to $10^3 M_\odot \text{ yr}^{-1}$. This would lead to dramatic star formation rates and very peaked X-ray surface brightness profiles. The ob-

served CC show much more gentle cooling rates, $1 - 10\%$ of the pure cooling flow value (For a review, see Gaspari 2015 and refs. therein). In contrast to NCC clusters, observed CCs typically have central temperatures $2 - 3$ times smaller than the virial value, where entropy starts to flatten (McNamara & Nulsen 2007, 2012). Mechanical AGN feedback is the current best model to explain the quenching of pure cooling flows, although other forms of heating may contribute (e.g., thermal conduction and cosmic rays; McNamara & Nulsen 2007, 2012 for reviews). Cool cores are indeed correlated with the presence of X-ray cavities inflated by AGN outflows (e.g., Hlavacek-Larrondo et al. 2015), low central entropy/cooling times (Cavagnolo et al. 2008), large H α luminosity (e.g., Voit & Donahue 2015) and multiphase gas down to the molecular regime (e.g., Tremblay et al. 2016). Such residual cooling gas is the main triggering mechanism of the AGN, leading to a tight self-regulated loop between CC condensation and AGN feedback energy (e.g., Gaspari et al. 2016 and refs. therein).

Hydrodynamic simulations on scales of both individual halos and cosmological volumes have improved through the introduction of sub-grid physics models for various forms of feedback. However, simulating all the relevant scales for these feedback processes is still a prodigious numerical challenge (Borgani & Kravtsov 2011, and references therein). A considerable amount of numerical effort has been spent on understanding the suppression of cooling flows via feedback mechanisms (e.g., Heinz et al. 2006; Sijacki & Springel 2006; Dubois et al. 2010; Battaglia et al. 2010; Gaspari et al. 2011; McCarthy et al. 2011; Martizzi et al. 2012; Li & Bryan 2014; Steinborn et al. 2015; Li et al. 2015). Recent simulations have been able to create a diverse sample of CC and NCC clusters (Rasia et al. 2015; Hahn et al. 2015). However, the

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cosmological hydrodynamic simulations are still significantly limited by the poor resolution within the CC region, which is crucial to properly track the AGN heating distribution and turbulent mixing properties, as shown in previous high-resolution simulations of isolated clusters (e.g., Gaspari et al. 2011, 2014a). The question remains, what is the physical origin of the difference between CC and NCC clusters? were they created under different physical conditions to begin with, or are NCC simply disturbed CC that have not yet had the time to cool back down?

There are two scenarios for how CC and NCC form and evolve – *external* or *internal*. In the external scenario, outside factors such as the large-scale structure would play a central role in determining the fate of clusters ab initio. In this model, NCC would typically be found in denser environments, whereby merger activity can pre-heat the clusters to higher levels ($\sim 300 \text{ Kev cm}^2$) (McCarthy et al. 2011). CC, on the other hand, would tend to form in isolation. In the internal scenario, only the immediate (inside; $\sim 1 \text{ Mpc}/h$) environment acts to transform CC to NCC. Here, breaking the tight self-regulated AGN-feedback loop results in overheating the core and raising the central cooling time well above the Hubble time (Gaspari et al. 2014b). Since in this case AGN heating should be unrealistically strong, it is more plausible that infalling substructures within the cluster (Sander-son et al. 2006, 2009; Leccardi et al. 2010; Rossetti & Molendi 2010; Rossetti et al. 2011; Eckert et al. 2014) are responsible for breaking the loop, thus inducing the NCC state.

To test how much large-scale environment plays a role in shaping these cluster cores, one can exploit galaxy clustering. The clustering of collapsed halos is enhanced relative to the dark matter distribution, an effect known as bias (Kaiser 1984; Efsthathiou et al. 1988; Cole & Kaiser 1989; Bond et al. 1991; Mo & White 1996; Sheth & Tormen 1999). This bias depends mostly on halo mass, making galaxy clusters highly biased (Kaiser 1984; Bahcall & Soneira 1983). However, numerical simulations show there is an additional but weaker dependence on the formation histories of the halos, an effect which is referred to as *assembly bias* (Gao et al. 2005; Wechsler et al. 2006; Wetzel et al. 2007; Jing et al. 2007; Gao & White 2007; Angulo et al. 2008). On cluster-mass scales, one predicts that late forming (low-concentration) objects of a given mass are more clustered (Wechsler et al. 2006; Jing et al. 2007; Wang et al. 2007; Zentner 2007; Dalal et al. 2008), but the effect is expected to be even weaker than on galaxy scales (Gao et al. 2005). Assembly bias has been difficult to demonstrate conclusively in observations, as it requires identifying samples that have similar halo mass, but which differ in assembly histories. A handful of observational studies have tried to measure assembly bias in the regime of groups (Yang et al. 2006; Wang et al. 2013; Lacerna et al. 2014) and of clusters (Miyatake et al. 2016; More et al. 2016). However, Lin et al. (2016) argue that the claimed detections of assembly bias on group scales could be attributed to samples of different halo mass or contamination by satellite galaxies rather than assembly bias. So far, attempts to detect assembly bias have divided cluster samples according to halo concentration as a formation epoch proxy (Miyatake et al. 2016; More et al. 2016), as higher-concentration is linked with ear-

lier formation in numerical simulations (Duffy et al. 2008; Bhattacharya et al. 2011). No study has yet attempted to detect it for halos of different X-ray properties such as entropy.

In this paper, we make use of spatial cross-correlations between galaxies and galaxy clusters to explore the large-scale environments, and hence, the assembly bias of CC versus NCC clusters. We use a statistical sample of clusters with information on their entropic core state from the ACCEPT compilation (Cavagnolo et al. 2009). This paper is organized as follows. In Section 2 we present the observational dataset used. In Section 3 we lay out our CCF methodology and show how to derive a relative bias. In Section 4 we present our results, and in Section 5 we forecast the improvement to our results with larger cluster samples. We summarize and conclude in Section 6. Throughout the paper, we adopt a Λ CDM cosmological model, where $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, and $h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1} = 1$.

2. DATA

We compare the clustering of two subsets of galaxy clusters – CC and NCC. Since our cluster samples are small ($\lesssim 30$ clusters in each, see below), the auto-correlation will be very noisy, so instead we perform a cross-correlation of each cluster sample with a parent galaxy sample. In this section we present the cluster and galaxy samples.

2.1. ACCEPT Cluster samples

The largest publicly available homogeneous compilation of X-ray clusters with high resolution radial entropy profiles⁴ has been presented in Cavagnolo et al. (2009)⁵, known as “Archive of Chandra Cluster Entropy Profile Tables” (ACCEPT). This sample consists of all 241 clusters that have been observed with the Chandra X-ray telescope with enough counts for a reliable entropy determination (each cluster temperature profile has at least three concentric radial annular bins containing a minimum of 2500 source counts each), and were in the archive as of 2008⁶. Cavagnolo et al. found that most ICM entropy profiles are well fitted by a model that approaches a constant value at small radii ($\lesssim 100 \text{ kpc}$), K_0 , which quantifies the typical excess of the core entropy. The distribution of K_0 is shown to be bimodal, with a distinct gap between $K_0 \approx 30 - 50 \text{ keV cm}^2$ and population peaks at $K_0 \sim 15 \text{ keV cm}^2$ and $K_0 \sim 150 \text{ keV cm}^2$. These relate to two populations, the former having short cooling times which we refer to as CC clusters, and the latter having longer cooling times which we refer to as NCC. Here we define two ACCEPT CC/NCC cluster subsamples, dividing at $K_0 = 40 \text{ keV cm}^2$. The chosen boundary translates to a typical cooling time of 0.8 Gyrs

⁴ There is a larger compilation of X-ray clusters drawn from Chandra, the ROSAT All-Sky Survey (RASS), and XMM-Newton (Piffaretti et al. 2011), but the latter two lack the high spatial resolution that Chandra provides to allow for homogeneous CC/NCC classification.

⁵ <http://www.pa.msu.edu/astro/MC2/accept/>

⁶ Many clusters have since been observed with Chandra, and an ACCEPT-2 compilation (M. Donahue, private communication) of entropy profiles is being prepared and will be utilized in a future paper.

(see Eq. (9) in Cavagnolo et al. 2009). ACCEPT clusters appear evenly distributed over the sky (Fig. 1; CC in blue and NCC in red), and span redshifts in the range $0.05 < z < 1.1$ (see the redshift distribution in Fig. 2).

2.2. LOWZ galaxy sample

For the large parent sample we use the LOWZ spectroscopic-redshift galaxy catalog⁷ (Reid et al. 2016), which is drawn from the Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. 2013). BOSS is part of Sloan Digital Sky Survey (SDSS; Eisenstein et al. 2011) III project Data Release 12 (DR12; Alam et al. 2015). The LOWZ sample is designed to extend the SDSS-I/II (York et al. 2000) Cut I luminous red galaxy (LRG) sample (Eisenstein et al. 2001) to $z \approx 0.4$ and fainter luminosities, in order to increase the number density of LRGs by roughly a factor of 3. In DR12 the survey is complete, covering both the north Galactic pole (NGC) and south Galactic pole (SGC), with a total effective area of 8337 deg², and containing 463 044 galaxies with spectroscopic redshifts (Reid et al. 2016). The sample distribution over the sky is presented in Fig. 1 (gray) and its redshift distribution is presented in Fig. 2 (gray). In recent analyses of LOWZ (Reid et al. 2016; Cuesta et al. 2016), the redshift range used was limited to $0.15 < z < 0.43$, resulting in a total of 361 762 galaxies. The sample is close to volume-limited (constant space density at $\sim 3 \times 10^4 h^3 \text{ Mpc}^3$) over the redshift range $0.2 < z < 0.4$ (Reid et al. 2016). We describe below the redshift limits we determine to maximize the use of the cluster sample.

2.3. Catalog spatial and redshift limits

We limit our cluster and galaxy catalogs such that they span the same sky area and redshift range for our cross-correlation measurement. In Fig. 1 we present the spatial distribution of all LOWZ galaxies (gray) and ACCEPT clusters (red+blue points). 102 of the 241 ACCEPT clusters are found within the BOSS NGC and SGC regions. Secondly, we present the redshift distribution of the LOWZ galaxies (gray) and ACCEPT clusters found in BOSS footprint (CC in blue and NCC in red) in Fig. 2. The LOWZ sample is typically analyzed within the $0.15 < z < 0.43$ range, where its selection function is reasonably uniform and well understood. The completeness of the LOWZ sample appears robust to $z = 0.1$, so we choose here to expand the low-redshift limit to $z > 0.1$ to overlap with low-redshift ACCEPT clusters. We note a similar lower limit has been used for other cluster sample analysis using SDSS, namely the redMaPPer cluster catalog (Rykoff et al. 2014, 2016; Miyatake et al. 2016). Within the BOSS footprint and redshift range, $0.1 < z < 0.43$, there are 400 176 LOWZ galaxies and 57 ACCEPT clusters, out of which 22 are CC and 35 are NCC.

2.4. Mass difference

To leading order, halo bias depends on mass, thus, it is important to ensure that the two cluster samples have the same mean mass before any statement on assembly bias, a second order effect can be made. We match the

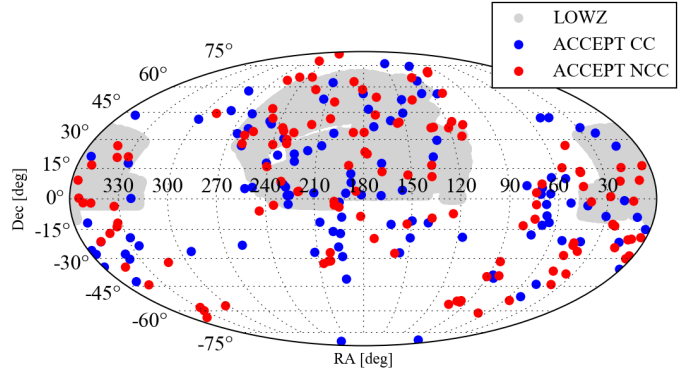


Figure 1. Sky distribution of the LOWZ galaxy sample (gray) and ACCEPT CC (blue) and NCC (red) clusters.

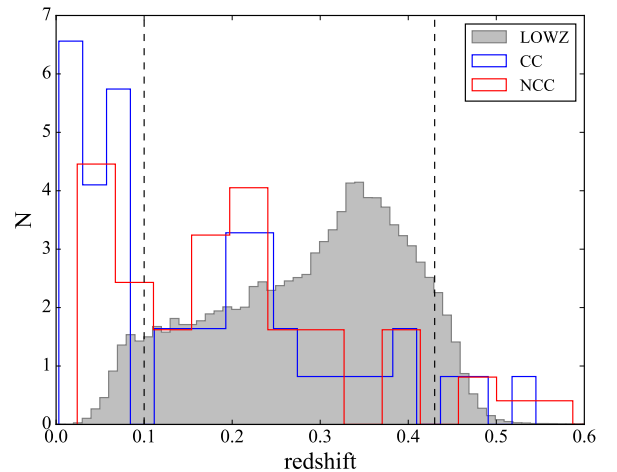


Figure 2. Redshift distribution of different samples: LOWZ galaxies (gray) and ACCEPT CC (blue) and NCC (red) clusters within BOSS FOV. The dashed vertical lines show our chosen redshift limits. Only 57 clusters are within the redshift range and BOSS footprint. The histograms are normalized for easier comparison. Within the redshift range chosen, the CC and NCC redshift distributions are statistically indistinguishable.

ACCEPT clusters that are within the BOSS footprint with the Planck SZ cluster sample (Planck Collaboration et al. 2016) and use the Planck SZ masses. We match 14 out of the 22 CC clusters, and 34 out of the 35 NCC clusters. The remaining clusters presumably fall below the Planck mass detection limit. We find that the ratio of mean masses as determined from the Planck SZ mass is $\langle M_{SZ,NCC} \rangle / \langle M_{SZ,CC} \rangle = 1.035 \pm 0.032$ for this sub-sample. The mass distributions of the two cluster samples are presented in Fig. 3. A Kolmogorov-Smirnov (KS) test confirms that the two subsamples masses are likely drawn from the same mass distribution, with $D_{KS} = 0.18$, and p-value of $p = 0.87$.

3. CROSS-CORRELATION FUNCTIONS AND RELATIVE BIAS

The two-point correlation function is a measure of how spatially clustered two populations are. One can formulate the probability above random of finding a galaxy in a volume element dV at a distance separation r from another galaxy as

$$dP(r) = n[1 + \xi(r)]dV \quad (1)$$

⁷ <https://data.sdss.org/sas/dr12/booss/lss/>

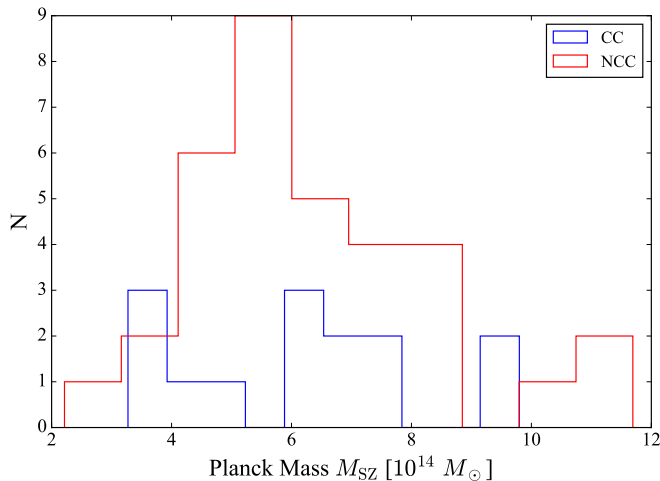


Figure 3. Mass distribution of 14 CC (blue) and 34 NCC (red) ACCEPT clusters within the BOSS FOV that are matched with Planck clusters.

where n is the mean number density and $\xi(r)$ is the two-point correlation function (Peebles 1980). If objects are distributed uniformly in space, $\xi(r) = 0$, whereas $\xi(r) > 0$ indicates clustering. The two-point CCF between galaxies and clusters in our case, relates to the probability as

$$dP(r) = n_g n_c [1 + \xi_{gc}(r)] dV_g dV_c, \quad (2)$$

where here n_g, n_c are the galaxy and cluster number densities. In the linear bias approximation, the galaxy auto-correlation function is related to the underlying dark-matter by $\xi_{gg}(r) = b_g^2 \xi_{DM}(r)$. For the galaxy-cluster CCF, this relation is in turn,

$$\xi_{gc}(r) = b_g b_c \xi_{DM}(r). \quad (3)$$

Since we correlate each of the two cluster samples (CC, NCC) with the same galaxy sample, the ratio of these cross-correlations simply traces the *relative* bias of NCC with respect to CC clusters,

$$b \equiv b_{NCC}/b_{CC} = \frac{\xi_{NCC}}{\xi_{CC}} \quad (4)$$

In order to estimate the 3D CCF, we count the number of galaxy-cluster pairs $D_g D_c(r)$, in bins of comoving separation, r , and compare with corresponding pair counts drawn from equivalent random galaxy and cluster catalogs, R_g, R_c , in each bin. We make use of the modified Landy & Szalay (1993, hereafter LS) estimator to calculate the CCF of these pairs,

$$\xi_{gc}(r) = \frac{D_g D_c(r) - D_g R_c(r) - D_c R_g(r) + R_c R_g(r)}{R_c R_g(r)}, \quad (5)$$

where each data and random catalog is normalized by its number density.

The selection function of clusters having Chandra observations is not defined, thus a cluster random catalog, R_c , is also impossible to construct. We instead simply match the sky and redshift distribution of the galaxy sample, as described above, and use the galaxy random catalog provided by Reid et al. (2016) for R_c . It is only important for the two cluster samples to be drawn from

the same distribution, since we are interested in the *ratio* between CC and NCC clustering. We show that the redshift distribution of the two cluster subsamples is similar in our chosen redshift range in Fig. 2. A KS test supports the two samples are drawn from the same redshift distributions within the redshift range $0.1 < z < 0.43$, with $D_{KS} = 0.2$ and a high p-value, $p = 0.6$.

4. RESULTS

We make use of the public code `swot`⁸ (Coupon et al. 2012) to calculate the CCF of ACCEPT clusters with LOWZ galaxies in 6 logarithmic bins spanning $3 - 80 \text{ Mpc}/h$. We note that above $3 \text{ Mpc}/h$ separation we are safely at the 2-halo regime, and thus avoid cross-correlating clusters with their own satellite galaxies. Finger-of-god effects are also not expected to be significant in this regime, as will be evident by the large errors on the resulting CCFs presented below. `swot` uses a descending k-d tree approach to cross-correlate catalogs, and has a lower opening angle threshold (OA) below which k-d trees are not further descended and large scale distances approximated to speed up processing time. We set $OA = 0.03$ radians, but find this has no effect on our results in the examined range, $r < 80 \text{ Mpc}/h$. The resulting CCFs are presented in Fig. 4 (left) for the CC subsample (blue circles) and for the NCC subsample (red triangles). The bias, given as the ratio of the two, is presented in the bottom panel. We compare LS with the Davis & Peebles (1983) estimator, and find the results identical.

By construction, adjacent bins of the correlation function are highly correlated, especially at large separations. Therefore, the use of Poisson errors underestimate the true variance on the large scales examined here. There are many different approaches in the literature to account for this covariance. One popular way is to divide the sky into equal subregions and derive the covariance using the “jackknife” method (Miyatake et al. 2016; Mountrichas et al. 2009, 2016). Another is to perform the calculation over many mock simulations that mimic the samples at hand (see, e.g., Blake et al. 2006; Knobel et al. 2012). Theoretically, mock simulations are preferred, as the jackknife value distribution is not Gaussian for a small sample like the one presented here. Furthermore, the largest separation that can be probed is limited by the jackknife region size, since large-scale modes are not probed by the smaller jackknife box (Norberg et al. 2009). The errors on all quantities are therefore derived using simulations, where we cross-correlate samples of mock galaxies and clusters of sizes comparable to the data at hand (for full details of the simulations and error analysis, see Appendix A).

As is evident from the size of the errors in the left panel of Fig. 4, the ratio of CCFs at large scales ($\gtrsim 25 \text{ Mpc}/h$) is noisy, as it is dividing two small quantities – the CCF at these scales approaches zero. When considering the full covariance derived from the simulations (presented in the right panel of Fig. 4), the mean relative bias is $\langle b \rangle = 1.42 \pm 0.35$, with a significance of 1.6σ relative to $b = 1$. In short, within the large uncertainty, we currently do not find a significant difference in the clustering around NCC and CC clusters.

⁸ <http://jeancoupon.com/swot>

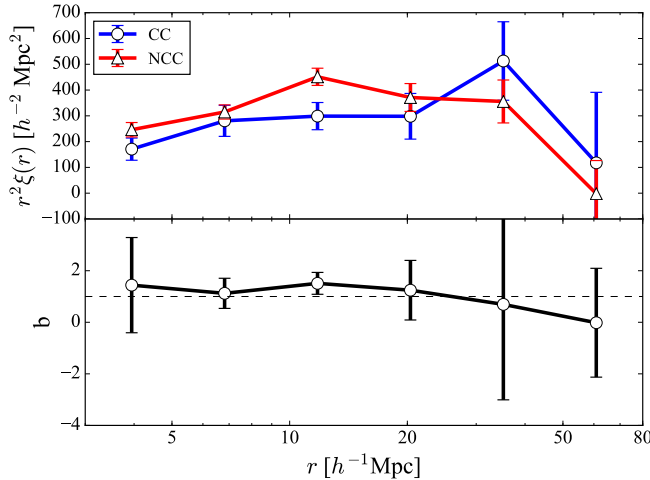


Figure 4. 3D Left: CCFs between LOWZ galaxies and two cluster subsamples: CC clusters (blue curve+circles) and NCC clusters (red curve+triangles). Bottom panel shows the ratio of NCC to CC correlations, which gives the relative bias, b . Errors are drawn from the scatter of 50 mock MICE CCF and bias measurements (same errors as in Fig. A1, left; see Appendix A for details). Right: Correlation coefficients of the bias determined from the simulations covariance matrix.

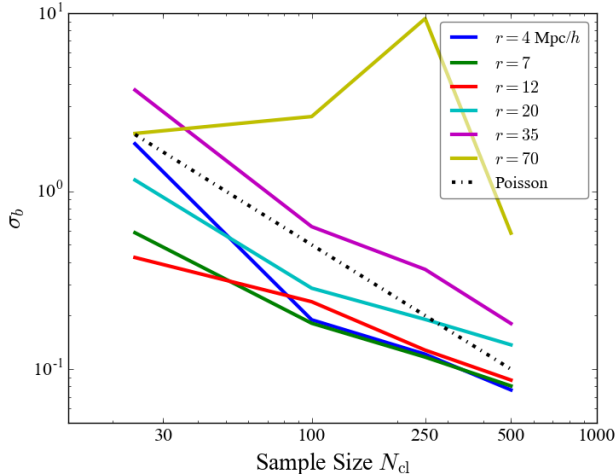


Figure 5. Error in the bias derived from simulations (solid lines) as a function of mock cluster sample size, plotted for each separation scale separately (different colors), as noted in the legend. The expected Poisson error scaling, \sqrt{N} , is shown as the dash-dotted line (with arbitrary amplitude).

5. FORECAST

We find that the average bias is determined at the $\Delta b/b \approx 0.35/1.42 = 25\%$ level. Although cross-correlating with a large galaxy sample allowed us to analyze a small cluster sample ($\langle N_{cl} \rangle \sim 24$), our analysis is still mostly limited by the small number of clusters with central entropy measurements. Here we forecast how a larger cluster sample will help improve this statistic. We perform the same mock analysis using simulations as described in Appendix A, for increasing numbers of mock clusters, $N_{cl} = 100, 250, 500$, in each subsample. In Fig. 5 we plot the size of bias errors, derived from the covariance of 50 mock simulations, as a function of cluster sample size. We plot this as a function of scale, r . The expected slope of this relation according to Poisson statistics, $-1/2$, is overlaid to guide the eye (black dash-dotted line). For $r \lesssim 35 \text{ Mpc}/h$, the errors roughly follow the Poisson expectation, but at $70 \text{ Mpc}/h$ they

do not. Following this scaling, a future sample of 500 clusters in each CC/NCC subsample will lead to a constraint on the bias that is $\lesssim 5\%$, and best probed over scales $r \lesssim 20 \text{ Mpc}/h$.

The level of assembly bias we find is in statistical agreement with the level found by Miyatake et al. (2016), $b = 1.41 \pm 0.09$. The main differences between these two measurements are the cluster samples, and how those samples are subdivided. In Miyatake et al. (2016) they use cluster galaxy member concentration as a proxy for their formation histories. Simulations predict the level of bias to be ~ 1.2 (Wechsler et al. 2006; More et al. 2016). Assuming this level of bias, with ~ 500 clusters in each subsample we can make a significant detection of assembly bias using our method at the 3σ level.

6. DISCUSSION & CONCLUSIONS

We have presented in this paper a methodology meant to explore the origin of the CC-NCC dichotomy. We compared the clustering of BOSS/LOWZ galaxies around CC and NCC cluster samples. By comparing these CCFs, we constrain the relative assembly bias of NCC with respect to CC clusters to be $\langle b \rangle = 1.42 \pm 0.35$, only 1.6σ above unity (a null detection). Limited by the small number of clusters in our subsamples (14 CC and 34 NCC), we do not detect a significant difference between the large-scale environments of CC and NCC clusters.

The main limitation of the current proposed method is the number of clusters with resolved X-ray cores available. We note that our study was done with a sample of Chandra X-ray clusters compiled nearly a decade ago. Since then, many follow-up Chandra cluster observations have been carried out, in particular targeting the Planck $z < 0.35$ clusters (Jones 2012). An updated compilation of cluster entropy profiles is currently being prepared, and will increase the number of clusters from ~ 200 (ACCEPT) to at least ~ 500 (ACCEPT-2; M. Donahue private communication). Currently, no future X-ray mission is under development to succeed the high-resolution Chandra Observatory. Only one mission

with sub-arcsec resolution, the X-ray surveyor⁹, is under conceptual consideration but may take over a decade to launch.

In the near future several wide-field spectroscopic surveys (e.g., eBOSS, Dawson et al. 2016; PFS, Takada et al. 2014; DESI¹⁰, Levi et al. 2013; J-PAS¹¹, Benitez et al. 2014) will provide galaxy catalogs to higher redshifts, allowing more clusters to be considered, although the yield of high-redshift clusters in the X-ray is not high. Alternatively, a southern redshift survey with BOSS-like depth could easily allow us to double the number of clusters in our analysis, as many of the X-ray clusters in ACCEPT are in the southern hemisphere (see Fig. 1). Unfortunately, no such redshift survey to sufficient depth currently exists, although the proposed satellite all-sky redshift survey SPHEREx (Doré et al. 2016) or the planned Euclid survey (Laureijs et al. 2011) could fill in the void. Using simple arguments drawn from a careful analysis of mock simulations, we showed that with a sample of 500 CC and 500 NCC clusters, for which a successor to Chandra is crucial, one can improve the measurement presented here from $\Delta b/b = 0.25$ to $\Delta b/b = 0.05$, and rule out (or corroborate) the role of large-scale environment in the creation of the CC/NCC bimodality.

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APPENDIX

A. ERRORS FROM MOCK SIMULATIONS

Resampling (e.g., jackknife) correlation functions when using small samples can be unrepresentative, and we opt

to instead use mock simulations to estimate and explore the behavior errors on the bias measurement, as determined from the ratio of CCFs. To that aim, we use the large N-body simulation from the Marenstrum Institut de Ciències de l’Espai (MICE) collaboration, the MICE Grand Challenge (MICE-GC) (Fosalba et al. 2015a,b; Crocce et al. 2015; Carretero et al. 2015; Hoffmann et al. 2015). The galaxy catalog was generated using a hybrid of Halo Occupation Distribution (HOD) and Halo Abundance Matching (HAM) prescriptions to populate Friends of Friends (FoF) dark matter halos from the MICE-GC N-body simulation¹².

We select both a galaxy and a cluster catalog from the full catalog, by limiting both to $0.1 < z < 0.43$, as in our data. We furthermore apply the color selection criteria applied to LOWZ (Reid et al. 2016) using the mock MICE g,r,i magnitudes in the creation of a mock galaxy sample. For the mock cluster samples we require that the galaxy is central (flag==0). The ACCEPT clusters are massive, spanning $14.4 < \log(M/M_\odot) < 15.1$, so that there are not enough massive simulated clusters in MICE to make a statistically large mock cluster sample from which multiple mocks can be drawn, that still match the observed mass distribution of our CC/NCC clusters. Instead, we construct the cluster sample to have a similar mass distributions as that of our clusters, but at a lower mass range, $13.5 < \log(M/M_\odot) < 14.6$. We furthermore divide them up equally into two distinct cluster samples, cl_A and cl_B , since we are interested in the ratio of CCFs that are of **independent** clusters. We then randomly select 14 clusters from cl_A and 34 clusters from cl_B , the same size as our CC/NCC samples. We repeat this process to produce 50 mock cluster sets. As with the data, we then calculate the CCF of each cluster sample and the mock galaxy catalog.

For the calculation, we produce a random galaxy catalog by drawing a random sample of galaxies on a sphere using VENICE¹³ with the same redshift distribution of the MICE-LOWZ mock galaxies (we verify that the construction of the cluster random is not important and its effect cancels out). A simulated “bias” is then constructed from the ratio between any two CCFs, $b_{i,j}(r) = \xi_{i,cl_B,g}(r)/\xi_{j,cl_A,g}(r)$ (2500 ratios in total). The error on the bias is simply the covariance of these 2500 simulated bias measurements. The mean CCFs and their covariance, along with the mean bias and its covariance, are plotted in Fig A1 (left, lower and upper panels, respectively). The covariance of the simulated bias is then used as uncertainty on the bias measured from the data (see Fig. 4).

To explore how the errors scale with increasing number of clusters, we repeat the above test using samples of $N_{cl} = 100, 250$ and 500 clusters in each mock cluster subsample. In Fig. A1 (right) we present the CCFs and bias estimated using 500 clusters, to demonstrate how we can improve our constraints on the bias. For both small and large samples of clusters, the measured bias is consistent with a null bias ($b = 1$) within the errors, as expected.

As discussed above, we selected mock clusters that are

⁹ <http://wwwastro.msfc.nasa.gov/xrs/>

¹⁰ <http://desi.lbl.gov/>

¹¹ <http://www.j-pas.org/>

¹² <http://cosmohub.pic.es/#/catalogs/MICECAT%20v1.0/prebuilt>

¹³ <http://github.com/jcoupon/venice>

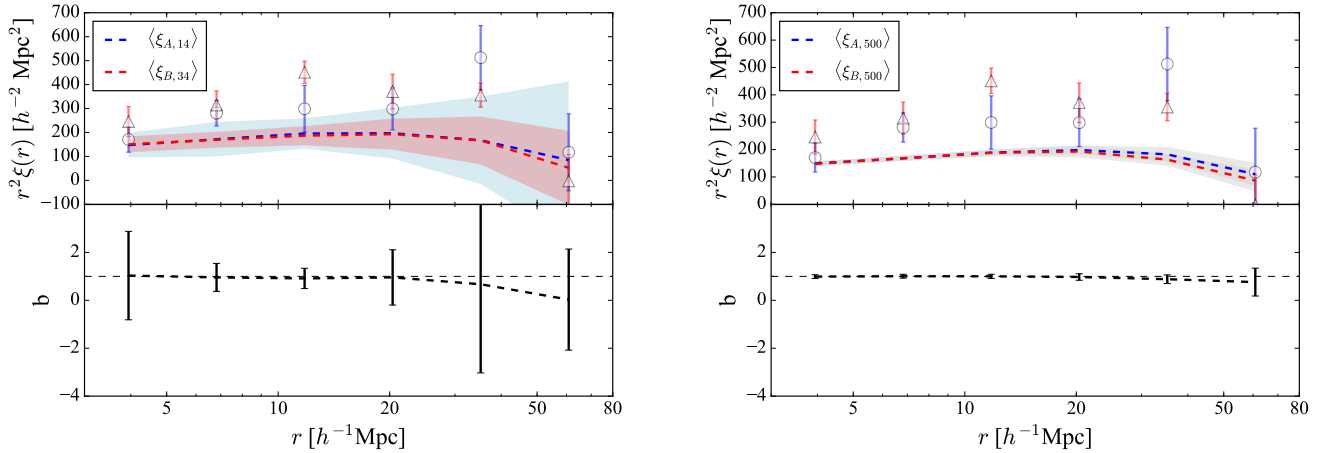


Figure A1. Results from 50 mock simulations, using combinations of 14 and 34 cluster subsamples as in our dataset (left), and using two subsamples of 500 clusters in each (right). Top panels show the CCF for the data (CC as circles and NCC as triangles) and for the simulations (dashed curve). Shaded regions represent the scatter from the simulations. Bottom panels present the bias as determined from the ratio of the simulated CCFs. Errors on the plots are derived from the diagonal part of the covariance matrix.

less massive than the real clusters. For this reason, the resulting simulated CCFs (dashed curves with shaded regions) have lower amplitudes than the real CCFs (circles with errorbars) in Fig. A1. This, however, does not affect the desired quantity, i.e. the bias between the two, as long as they have similar mass distributions.

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